SPECIFICATIONS OF DRILLING REQUIREMENTS FOR THE APOLLO LUNAR SURFACE DRILL USING BORON REINFORCED FIBER GLASS

Marcus G. Langseth
Richard Perry

Lamont-Doherty Geological Observatory
of Columbia University
Palisades, New York

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THE DRILLING REQUIREMENTS OF THE ALSD FOR THE LUNAR HEAT FLOW EXPERIMENT

Marcus G. Langseth, Jr.

I. Introduction:

The primary objective of the ALSD is to drill two 3-meter holes in the lunar subsurface in which the temperature probes of the lunar heat flow experiment will be placed. A second objective is to obtain samples of the lunar subsurface to depths of 3 meters. Ideally a complete and continuous sample of the subsurface drilled should be obtained.

From the start of development of the ALSD the design has been strongly constrained by several factors. The most important are listed below:

1. The physical properties of the lunar surface and subsurface material down to 3 meters.
2. The lunar surface environment.
3. The thermal requirements of the HFE.
4. The spacecraft weight and volume constraints.
5. The mobility and life-support capacity of the extra vehicular mobility unit (space suit).
6. The time available for emplacement of the heat-flow experiment (HFE) during lunar surface excursions.

Of the six factors the first was by far the least well-known at the time that development was begun. As a consequence the design of the drill was such as to accomplish the objectives in as broad a spectrum of material as possible. However each of the constraints listed above has an important impact on the others. For example, the hardness of the lunar subsurface materials determines the amount of energy required to drill the holes. Therefore, for a given power for the drill, the time to accomplish the task is determined as well as the amount of heat which must be dissipated to maintain the drill at operable temperatures. Similarly the cohesion of the subsurface material has an important bearing on the design since in poorly-cohesive materials the walls of the hole will collapse if and when the drill is extracted.

The information provided by the successful Surveyor and Orbiter missions of 1966-67 has been analyzed by several groups and our knowledge of the nature of the uppermost several meters of the moon is many fold that of only two years ago. The purpose of this report is to review these recent findings from the point of view of drilling requirements of the ALSD with the objective of further optimizing the design and determining the models of subsurface materials in which the drill should be tested and training procedures carried out.

II. <u>The nature of the lunar subsurface materials to a depth of 3 meters:</u>

a. <u>Processes shaping the surface layers:</u>

The extremely low pressures (10^{-13} atmospheres) and absence of surface water movements and vegetation results in far less variation in the characteristics of the moon's surface than on earth. One process seems to predominate in shaping the lunar surface. This process is the incessant rain of solid interplanetary particles on the surface. Some of these objects arrive at velocities up to 11 km/sec while most have somewhat lower speeds 2-4 km/sec. Lunar fragments that are on short trajectories after being kicked up by high velocity impact (secondary impacts) can have very low velocities.

The impact of high velocity objects is very similar to a high order chemical explosion. This explosion creates a crater whose diameter is proportional to the 1/3 power of the kinetic energy of the impacting particle. Material in close proximity to the explosion is fragmented and propelled out onto the lunar surface. Some material beneath the explosion is fragmented.

Over very long periods of time particles of widely different sizes rain down on the surface. The smaller sizes by far predominate. The distribution of mass of meteoric particles follows a curve very much like that shown in Figure 1.

If we imagine the lunar surface evolving under this process from an initially "fresh" flat surface of solid rock such as dense hard lava flow; then as time passes the surface will be transformed into a finely comminuted aggregate of rock fragments. At the start this pulverized layer, "debris layer" or regolith (Rennilson, 1966) will be extremely thin since the surface will have been hit everywhere by very small particles. With passing time however the surface will have been hit everywhere by increasingly more energetic impacts and the regolith slowly grows deeper.

When the regolith is still shallow, the occasional large impact will throw sizeable fragments out onto the surface; these blocks once exposed will in turn be slowly eroded by the rain of smaller objects.

In their report of television observations from Surveyor VI Morris et al. (1968) discuss this evolution in some detail. They point out that the thickness of the regolith on the lunar surface will be related to its

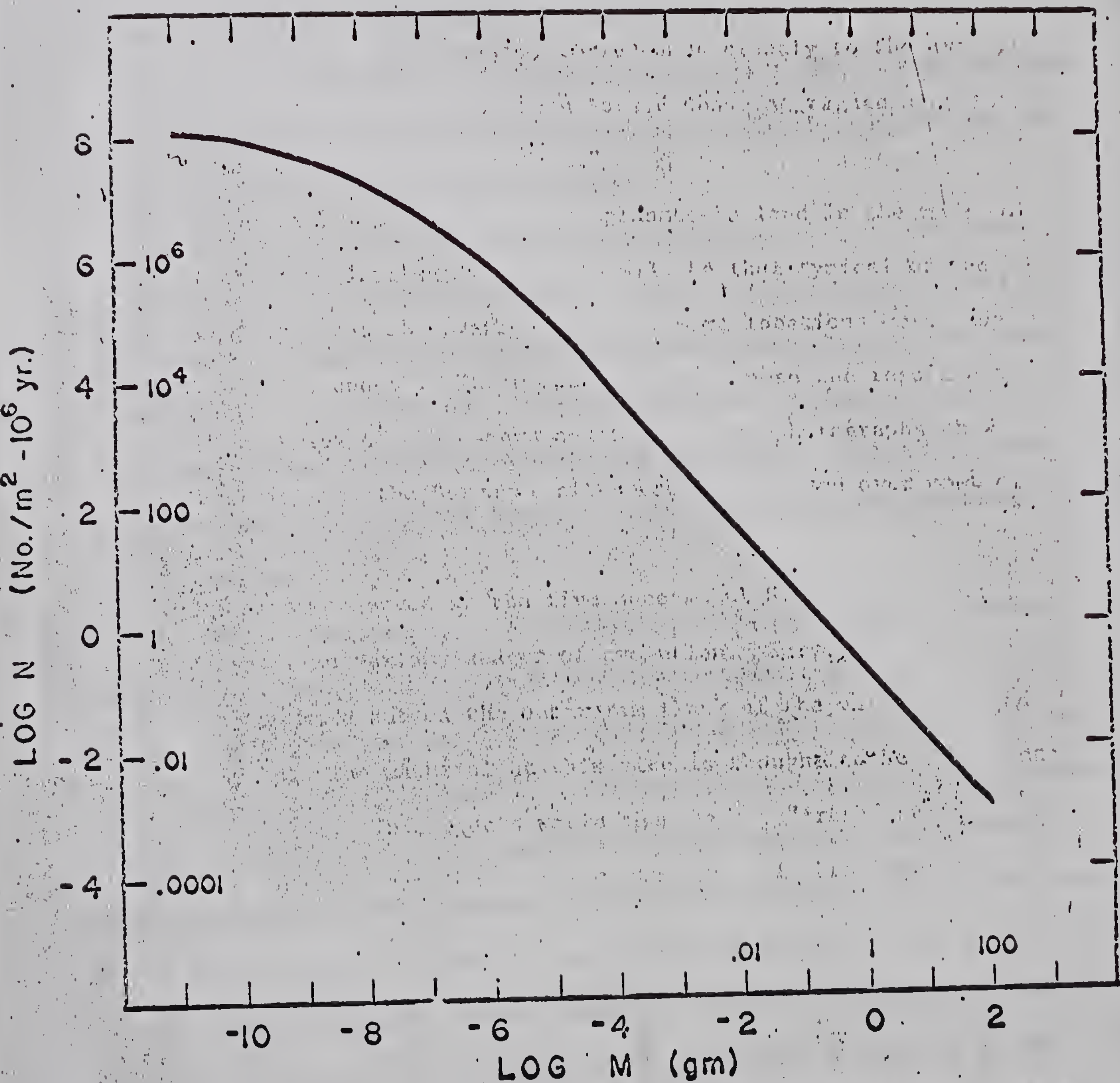


Figure The cumulative flux distribution of meteoritic mass about the earth (after Naumann, 1966).

age. One can define a theoretical or expected depth.

"This depth (that of the regolith) corresponds closely to the average depth of the large craters that have been formed whose aggregate area is equal to the area of a given mare surface."

The early Apollo landing missions are planned to land in the mare so that the regolith to be drilled by the ALSD will be that typical of the mare surfaces. Close hand observations of four mare locations were made by Surveyors I, III, V and VI. These observations showed the regolith to be pervasive within view of the camera and the Orbiter photographs show the local observations at the Surveyor sites can be extended over most of the mare surfaces.

The debris layer observed at the five successful Surveyor landing sites are apparently in various stages of evolution. Surveyor VII was located, not in the mare but on the outer rim flank of the very large and recent crater Tycho. The material at this site is thought to be the ejecta blanket of this crater. This ejecta would then be the "fresh" surface which subsequent to the formation of the crater Tycho is being pulverized into a debris layer. The debris layer around Surveyor VII was observed to be only several cm thick. At the Surveyor I site the thickness of the debris layer was about 1 to 1½ meters thick, whereas, at Surveyor VI site the debris was determined to be greater than 10 m thick.

From the foregoing scheme of regolith evolution one could suggest that the surface at each Surveyor site described above is progressively older.

b. <u>The nature of the regolith:</u>

We have already concluded that the regolith consists of highly comminuted rock which we would expect to find in more dense, perhaps crystalline, form at depth. The evidence we have available on particle size distribution in the regolith comes from counts of the exposed fragments on the surface. The camera can resolve particles down to 1 and 2 mm in diameter near the base of the spacecraft. A typical result of such counts is shown in Figure 3-41 of the Surveyor VII report (Shoemaker, 1968). This figure is a graph plotting the number of particles above a certain size, y, in a 100 m^2 area of the surface. The results from areas near and distant to the camera generally fit straight lines on a log-log plot indicating a close fit to power law distribution of the form:

$$N_a = Cy^{-\lambda} \qquad \text{(Eg. 1)}$$

Where N_a is the cummulative number of particles with a diameter greater than y within a 100 m^2 area. λ is given by the slope of the straight line and C by the intercept at a 1 meter particle size. At the Surveyor VI site for example $\lambda = 1.8$ and $C = 3.15$. The Surveyor reports give the intercept at a particle size of 1 mm, however for this report we find using meters more advantageous for calculation.

To investigate the problem of drilling through the regolith it is important to try to translate this information into the distribution of material within a volume. Although we have very scant information about the distribution of particles with depth, we might at the start assume that the distribution with depth is well represented by the surface distribution. We shall mean by this that the proportion of a unit area covered by particles of average size, y_i, in a narrow range, Δy, is equal to the proportion of a unit volume occupied by the same sized particles. Further let's assume that the particles are spherical. Then the above assumptions can be formulated as:

$$\Delta N_v \cdot \frac{1}{6} \Pi \, y_i \; 3/L_3 = \Delta N_a \frac{\Pi}{4} y_i \; 2/L_3.$$

ΔN_v and ΔN_a are the number of particles in the size range Δy per unit volume and area respectively.

Therefore: $$\Delta N_v = \frac{3L\Delta N_a}{2y_i}$$

From this simple relation it is possible to convert the surface distribution of all particles into a volumetric distribution

$$N_v = \frac{3L}{2} \int_{y1}^{\infty} \frac{dN_a}{y}$$

From equation (1)

$$dN_a = -\lambda C y^{-\lambda-1} \, dy$$

Therefore $$N_v = 3L/2 \int_{y_1}^{\infty} -\lambda C y^{-\lambda-2} \, dy$$

$$N_v = \frac{3\cdot L\cdot\lambda\cdot C}{2\cdot(\lambda+1)} \cdot y1^{-\lambda-1} \qquad \text{(Eq. 2)}$$

which is valid for all cases except where $\lambda = 1$, then

$$N_v = \frac{-3\cdot L\lambda C}{2} \Big|_{ny}$$

c. Implications of the volumetric distribution at Surveyor sites:

We can get expressions for the volume occupied by particles within a certain size range by again assuming they are spherical. The volume occupied by a very narrow size range Δy is

$$dV = \frac{1}{6}\Pi\ y_1{}^3\ dN_v$$

so that $$V_{y_1<y<y_2} = \frac{3L}{2}\int_{y_1}^{y_2} \frac{1}{6}\ \Pi\lambda c y^{-\lambda+1}\ dy$$

or $$V = \frac{\Pi L\lambda c}{4(2-\lambda)}\ y^{-\lambda+2}\Big|_{y_1}^{y_2} \qquad \text{(\underline{Eg. 3})}$$

It is interesting to use these results to examine the implications of the distributions observed at each Surveyor site. In Table 1 we present the data for each of the five sites. The coefficients C and λ are given and the inferred thickness of the regolith. In addition the percent by volume of particles larger than 2.5 cm, 1 mm and 10 micron are given.

<u>Table 1</u>: The volume occupied by particles larger than 2.5, .1 and .001 cm in diameter based on the surface distributions observed at the Surveyor sites.

Surveyor Mission	Thickness of Regolith	C	λ	% Volume y>2.5	y>1 mm	y>10 microns
I	1-1.5 m	267	2.09	6.7	9.2	14.0
III	2-9 m	.0476	2.60	1.5	10.0	160.0
V	<5 m	.0158	2.62	.5	3.8	60.0
VI	>10 m	.0632	2.50	1.7	8.3	83.0
VII	<.1 m	3.15	1.80	11.6	16.6	20.0

This crude analysis points up some interesting features of the volumetric distribution of particle sizes. The proportion of large size particles correlates inversely with the regolith thickness and hence age of the surface. Sites III, V and VI all yield very similar results and suggest that the size distribution has nearly stabilized. In such mature regolith the particles larger than 2.5 cm represent only 1-2% of the volume and particles larger than 1 mm only about 10% by volume. Furthermore if the average porosity of the regolith is in general about 50% (appropriate for a density of 1.5 gm/cc) (Scott, 1967), then the volume requirements are well satisfied by particles larger than 10 microns. The analysis of the imprint of the Surveyor footpad shows the properties of the regolith are governed by the predominance of very small particles as our analysis also implies.

On the other hand the size distributions at sites I and VII have not stabilized. Particles above 2.5 cm form a relatively large proportion of the volume. Secondly at these sites the values of C and λ cannot hold for particles smaller than 1 mm or else much of the volume remains unaccounted for. This suggests that one distribution applies to the larger particles while another applies for those less than 1 mm, whereas in the more mature debris one function seems but is not necessarily adequate over the whole range of particles. It is important to note however that the surface distributions in the strewn field of relatively new craters at sites where the debris is "mature" have distributions more like sites I and VII. This is particularly noticeable at site III where the debris layer thins to about 1 m over the rim of a large crater.

These observations lead to the conclusion that the surface particle size distribution is directly related to the frequency with which impacts penetrate to the consolidated subsurface layer, and hence to regolith thickness.

We should now return to the question: Is the assumption that the surface distribution represents the distributions at depth reasonable? There are several reasons to expect that the proportion of large particles are greater at the surface than in the immediate subsurface.

1. The large sized particles on the surface represent ejecta from cratering of the consolidated substrate. Once on the surface these large rocks are continually pulverized by smaller particles. The slow erosion or rounding of surface blocks is evident in many of the Surveyor pictures. Thus on the surface one would expect to find the largest number of ejected boulders.

2. Steady settling of the regolith due to seismic movement of surface can produce a certain amount of sorting of particles. Usually larger particles work their way to the top after prolonged vibration. Elliot <u>et al.</u> (1967) suggest that large blocks may be stranded on the surface over ridges due to this sorting effect with the added impetus of gravity settling on a slope. This could be a direct observation that some settling occurs. The blocks moving toward the top of the regolith, of course, became more vulnerable to erosion.

These reasons suggest that, if anything, the proportion of large blocks may be smaller immediately below the surface. To a limited degree this conclusion is supported by the fact that at the Surveyor III site the mechanical soil sampler during the excavation of 10^4 cc of material did not uncover one solid particle capable of resolution by the camera. (Scott, personal communication.)

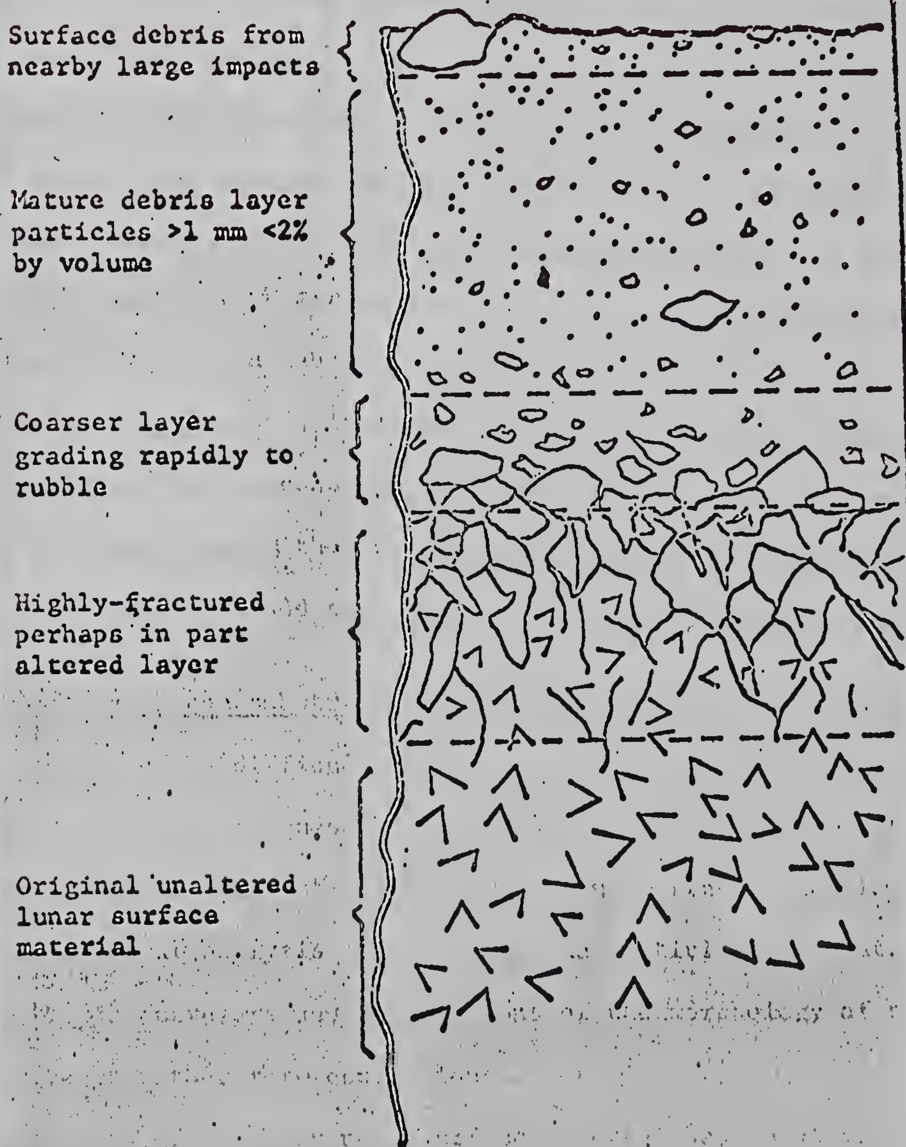
Near the bottom of the regolith however we can expect the proportion of large particles to increase. This results from the process by which the regolith grows deeper. It deepens by successively larger to larger impacts that are subsequently refilled. Consequently the near bottom material is not reworked as frequently as the upper parts of the regolith and the large fragments produced during the deepening impacts are not as finely comminuted. This layer of larger debris however must be relatively thin due to the steep slope of the impact energy curve (proportional to the mass curve in Figure 1).

To summarize: In areas of the moon where the regolith is thick enough so that an impact that reaches the consolidated subsurface are very infrequent, the size distribution has stabilized. This size distribution is probably typified by the debris layers at Surveyor III, V and VI sites. In these areas one can expect a rough stratification of the debris layer. This hypothetical stratification is shown in Figure 2. In Figure 2 it is suggested that the original surface was a dense crystalline rock such as basalt. The evolution of the regolith as envisioned here would lead to large proportions of the regolith having a size distribution similar to that seen in Surveyor VI.

d. <u>Lateral variation of the regolith and secondary effects</u>:

The impacting of meteoric material results in erosion of the topography of the lunar surface. This is most likely due to greater exposure of positive topographic features combined with gravity-driven down hill slumping and settling. Topography formed in the debris layer, such as a new crater, will erode in such a way that the regolith will thin over positive relief with time and thicken over depressions. This process has

Figure 2. Hypothetical stratification in a mature regolith on the maria floor.



been examined analytically by Ross (1968). The effect was clearly illustrated at the Surveyor III site. The spacecraft landed inside a crater 250 m in diameter and 15 m deep. Over the rim of the crater the debris layer was ostensibly about 1 m thick whereas in the center of the crater the debris was more than 9 m thick.

Secondly, many selenologists have conjectured that the density of the debris layer increases very rapidly with depth. Scott (1967) observed a definite increase in shear strength with depth when digging with the mechanical sampler. Most likely this results from an increase in compaction with depth due to gravity settling and impact compaction. However, once a porosity of 40 to 50% is reached, it is doubtful that the density becomes greater with depth until the consolidated subsurface is reached. Mechanical properties inferred from the survey show that most of the density gradient appears to be confined to the upper 10 cm of the debris layer.

e. The nature of the substrata and the blocks that make up the regolith:

To estimate the difficulty of drilling a ten-foot hole in the moon it is necessary to make some guess as to the nature of the rocks that make up the substrata and blocks that are visible on the surface. In view of the results of the chemical analysis made by an alpha particle back-scattering experiment on three Surveyors and implications of the morphology of the maria can now reach rather firm conclusions.

The composition of the very near surface material has relative abundances which are very nearly like those of volcanic basalts of the oceanic type found on earth. The data presented by Turkevich (1968) has been further analyzed by Jackson and Wilshire (1968) and they suggest that the relative abundances of elements best correspond with those of tholeiitic basalt most commonly found near the oceanic ridges. One very important property of oceanic basalts is their extremely low viscosity at near molten temperature. A material of remarkably low shear strength (nearly liquid) is required to explain the great flatness of the maria. To this author the flooding of the maria basins by basaltic lavas of the oceanic type is highly probable. These basalts would bear, one can imagine, a close resemblance to the flood basalts of Oregon and Arizona.

The upper surface of the lavas would be highly vesicular perhaps even frothy due to the escape of volatives into the void of space. But vesicles would probably decrease with depth in the flows. Evidence is very meager that other processes such as pumice or ash falls are common on the maria. The absence of features that might serve as vents seems to militate against these features being extensive in the maria. Lastly, the low gravitational force on the moon might favor sill formation rather than surface flows after the initial formation of a cooled solid crust. The rock composing these sill structures would probably not be vesicular and consequently vesicularity might by this argument be expected only near the upper surface of the maria floors.

This discussion is confined to areas of the maria at great distances from large impact craters. The virgin surfaces near large craters may be far more complex. Surveyor VII which landed on the ejected blanket of Tycho is a good example of such a complex area.

In the maria however one can anticipate that vesicular basalt will lie beneath the debris layer in a high proportion of the areas. Naturally the larger fragments on the surface would also be basaltic in composition.

however we can expect a large variation in physical nature. One might expect some blocks to be unaltered samples of the undisturbed substrata. Such blocks would most probably be vesicular basalt and in areas near a large crater some dense basalt. Many of the blocks however would probably be well-shattered samples of substrata and some of these may be slightly vitrified. In addition a certain percentage of the blocks may be rewelded debris. Impacting particles a few centimeters in diameter have enough energy to raise adjacent material to near molten temperatures, >1000° C, and thus reweld the fragments. Therefore the drillability of these fragments will vary greatly, the dense basalt being the most difficult while the impactites should drill quite easily.

III. <u>The Drill Requirements:</u>

From all of the foregoing it appears that the drilling difficulties can be well defined if we limit ourselves to emplacing the heat-flow experiment in the debris layer. All evidence indicates that this can be done with confidence if discrimination is used in selecting a landing site and the heat flow experiment emplacement site. For example if the mission on which the heat flow experiment is to be emplaced went to an older area of the maria such as Surveyor site III, V and VI, we would be assured of several meters of debris in which to drill. However, the astronaut must select a site which is away from positive relief features such as crater rims and ridges and instead select a broad (50 m) mildly depressed or flat area.

Beginning in such an area the astronaut would drill a ten-foot hole or until drilling rate slowed to 3-5 in/min. Should the rate slow during the drilldown of the first two sections, the drill should be retracted and a new hole started a few feet from the first attempt. However if the slow drill rate is encountered with three or more sections on the drill string, the astronaut is irretrievably committed to the hole and should continue drilling for a total of five minutes or to the full ten feet whichever comes first.

a. <u>The probability of hitting large fragments during drilling of the heat flow boreholes:</u>

With the constraints imposed on the drill it is not possible to design a drill that will guarantee a 100% chance of drilling two ten-foot holes. But one can well ask what kind of rock drilling capability must be taken to the moon to at least offer a 90 or 95% probability of getting two ten-foot holes?

To try to get some idea we can calculate the probability of hitting rocks of a certain size in the process of drilling. Since these calculations will only be used as a guide, they will be based on very simplified assumptions. These assumptions are:

1. The probability of hitting a rock of a certain size in a small size range, $y_i \rightarrow y_i + \Delta y$, during the drilling of a hole D meters deep is equal to the fraction of a unit surface area, L by L, covered by the projected cross-sectional areas of all particles of this size range in a volume L by L on the surface and D meters deep.

2. The above probability applies to a very thin drill. When the drill has a finite size, say a radius r, then the probability can be calculated giving each particle in the size range $(y_i \rightarrow y_i + \Delta y)$ a radius of influence equal to $y_i/2 + r$. Showing that the drill has to be within one radius of the drill centerline of the particle to hit it.

3. All particles are assumed to be spherical. In reality, of course, the particles have a large variety of shapes and the cross-sectional areas of such particles also vary. However, the circular cross section of a spherical particle represents 79% of the maximum possible area (represented by a square). Thus using a spherical shape does give a conservative estimate of probability.

From these assumptions we can generate a formula to give the probability. From equations 1 and 2:

$$P = \text{Average cross section area} \times \Delta N_V / L^2$$

or, $P = \frac{\pi}{4}(y_i + d)^2 \, dN_v/L^2$

where d = the diameter of drill. Earlier we saw that $|dN_v| = \frac{3D\lambda C y_i^{-\lambda-2}}{2} dy.$ Thus for a given size range, $y_1 < y < y_2$

$$P = \frac{\pi}{4L^2} \cdot \frac{3D}{2} \cdot \int_{y_1}^{y_2} \lambda C y^{-\lambda-2} \cdot (y + d)^2 \, dy.$$

Therefore,

$$P = \frac{3\pi DC}{8L^2} \left[\frac{\lambda}{1-\lambda} y^{1-\lambda} - 2dy^{-\lambda} - \frac{\lambda d^2}{\lambda+1} y^{-\lambda-1} \right]^{y_2}. \qquad \text{(Eg. 4)}$$

If $\lambda > 2$, then if $y_2 = \infty$

$$P = \frac{3\pi DC}{8L^2} \left(\frac{\lambda}{\lambda-1} y_1^{1-\lambda} + 2 \cdot d \cdot y_1^{-\lambda} + \frac{\lambda d^2}{\lambda+1} y_1^{-\lambda-1} \right)$$

The coefficients given earlier in Table 1 allow us to calculate roughly the probability of hitting rocks above a certain size based on the distribution observed at the Surveyor sites.

In Figure 3 we present graphically the results of applying equation 4 to the data from Surveyor I and VI. The curves shown give the probability (in percent) of hitting a fragment above a certain size. Notice that both scales are logarithmic. For example in a debris layer like that at the Surveyor VI site the probability of hitting a fragment larger than 25 cm (10 inches) is 3%, whereas at the Surveyor I site the probability is 9%. For particles smaller than 4 cm (1½") the probability is greater than 100% which simply means the drill is likely to hit more than one rock this size or less while drilling a 3 meter hole.

This approach indicates that if the drill taken to the moon had the capability of drilling a total of one meter thickness of rock with the

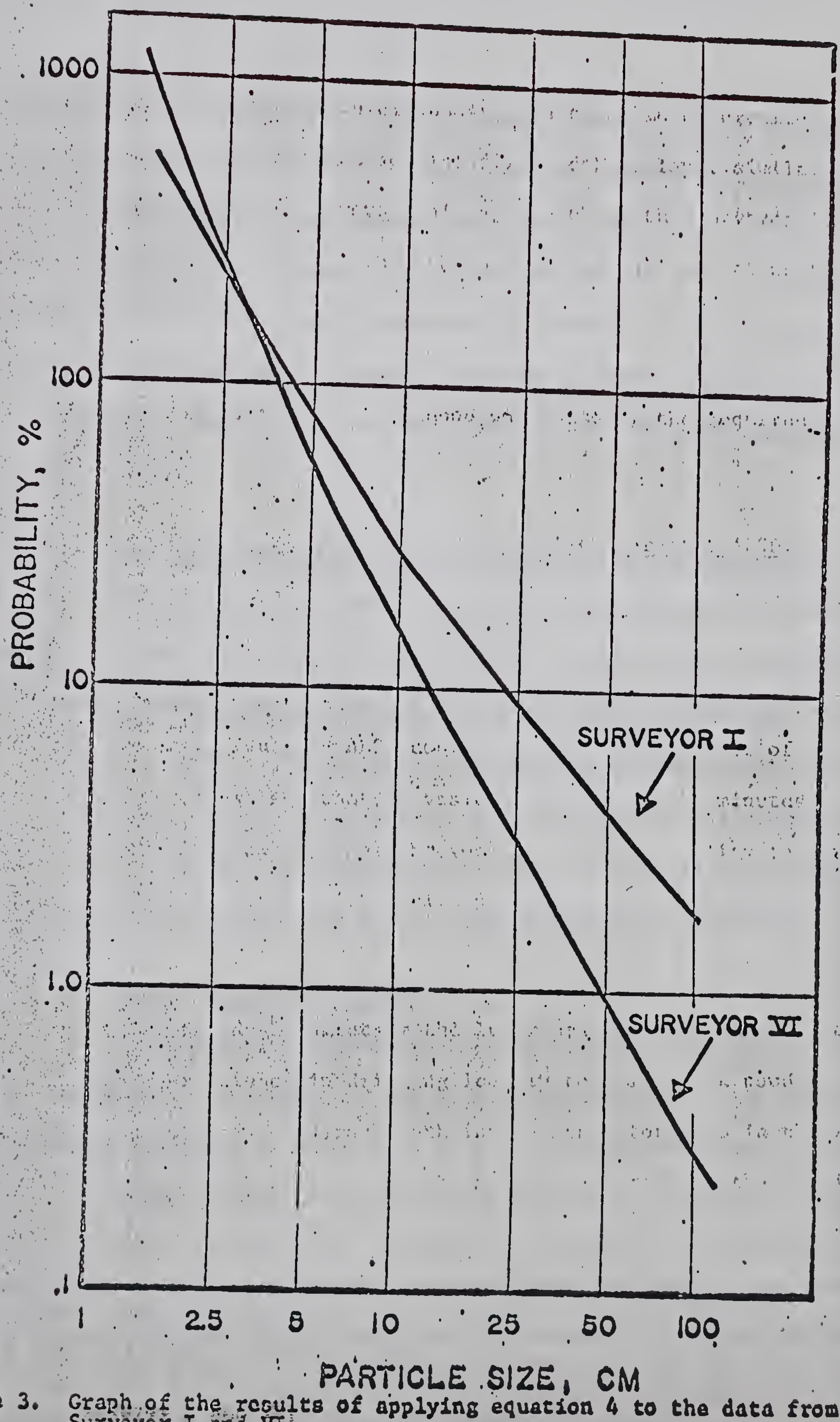


Figure 3. Graph of the results of applying equation 4 to the data from Surveyor I and VI.

strength and hardness of vesicular basalt, chance would be excellent, ~98%, that two 3 meter holes could be completed in a debris layer similar to that found at Surveyor VI site, however only about 86% at the Surveyor I site. A most important conclusion is that the probability of completing two holes 3 meters deep is not greatly improved by doubling the hard rock drill capacity. On the other hand it should be noted if there was little or no hard rock drilling capability, the likelihood of finishing the required drilling is very small.

b. <u>The hard rock drilling capabilities of the present ALSD</u>:

The present ALSD and the ALSD with the boron reinforced epoxy drill stem have drilling rates of about 2-4 cm/min in very dense basalt, 6.5 to 13 cm/min in vesicular basalt and 30 cm/min and greater for loosely consolidated rocks. Thus the ALSD could drill through a meter of rock whose average hardness like that of vesicular basalt in 10 minutes. Therefore, in our opinion the ALSD has the rock drilling capability to perform the heat flow drilling task with a high probability of success.

c. <u>Drilling the debris layer</u>:

During the development of the lunar heat flow drill we have gained considerable experience in drilling loosely cohesive rock powders with scattered fragments of solid rock both in the laboratory and in the field. How well these "models" represented the problem of drilling the debris layer on the moon is debatable. In general the models did not have so high a percentage of fine materials as are believed to exist in the lunar regolith nor is it possible to duplicate the interparticle adhesive properties of the fine rock powders that has been observed on the moon. (Scott, 1967.)

In development tests penetrating ten feet of non-adhesive bone-dry powders has not presented serious difficulties and a section of drill string (~20") can be drilled down in 20 seconds to one minute. At depths greater than two meters the torque required to turn the drill stem increases rapidly presumably due to wall friction. In the drilling laboratory models this torque did not exceed that of the slip-clutch in the power head (about 20 in/lb). However in field tests the presence of only a little moisture, which greatly increases interparticle adhesion, increased the wall friction so that the torque limit was exceeded. Usually the moist soil would cement between flutes of the drill preventing upward transport of cuttings and producing very high wall friction. In dry rock powders a very important factor in reducing wall friction is the agitation all along the stem produced by the percussive action. This action tends to keep the dust particles adjacent to the drill stem fluidized and thus reduces jamming.

In the powders as fine as those believed to make up the lunar regolith and which have a weak adhesion, is it possible that effects similar to those in moist soils will result in torques that will exceed the limit (20 in/lbs)? The adhesion between particles in a vacuum results from weak bonds between atoms of two particles in close contact. These forces are referred to as Van der Wald forces; they are quite weak and act over very short distances. They are therefore easily broken. The experiments with the soil sampler on Surveyors III and VII detected a very light adhesion but not enough to result in material sticking in the sampler scoop or prevent trenching.

The Surveyor TV indicated that many of the larger fragments were actually aggregates of much smaller particles, probably bound together by Van der Wald forces. We might infer from this that the powders disturbed and agitated by the drill will tend to form small very weak clumps (probably similar to those seen in the disturbed zone around the footpads) but they will not cement into a hard material in the manner that moist clayish soils do. However, in the models used for drill tests in the future we should increase the proportion of material that has particle sizes of less than 100 μ.

IV. Models of the lunar regolith for drill testing:

Make up a model that will nearly duplicate the estimated particle size distribution of the lunar regolith.

1. Because of the tendency of the smaller particles to fill the voids between the larger ones, the proportion of each particle size range should be done by weight.

2. The material to use is vesicular basalt--however, it is essential to use vesicular basalt only for those particles greater than .1 cm. Below this size any rock material may be used except such unique powders as talc, etc.

3. We want to make two mixes, one that is similar to Surveyor VI and one like Surveyor I.

4. The method to calculate the weight fraction of material is to first use expressions for particle size distribution to calculate the volume then use our estimated porosity to calculate the required weight.

5. For the Surveyor I site simulation the surface distribution at site I will be used for particles greater than 1 mm. And the Surveyor site VI for the remainder.

We showed earlier th... the volume, V, represented by particles in a size range, y_1-y_2 is

$$V = \frac{\Pi L}{4} \; \frac{\lambda C}{2-\lambda} \, y^{2-\lambda} \Bigg|_{y=y_1}^{y=y_2}$$

Since the equation giving V = f(y) applies to an area 100 m^2, the term L in the above equation can also be written $Vo/100m^2$ where Vo is the volume of the model. Therefore the weight of particles in the size range y_1-y_2 is

$$W = \rho \frac{\Pi V_o}{400} \cdot \frac{\lambda c}{2-\lambda} \cdot y^{2-\lambda} \Big|_{y=y_1}^{y=y_2},$$

and the percent of the total weight of the model is

$$W/W_o \cdot 100 = \frac{\Pi}{4(1-\alpha)} \frac{\lambda c}{2-\lambda} y^{2-\lambda} \Big|_{y=y_1}^{y=y_2},$$

since $W_o = \rho V_o(1-\alpha)$ α = porosity of the mix, usually about 60%.

With this equation we can make a plot like those shown in Figure 4, which shows in percent total weight, the weight of particles above a certain size y. At the far left end the curve is smoothed off to not exceed 100%. Notice the great difference in slope between Surveyor I and VI. It is clear as we noted before that the distribution at Surveyor site I cannot account for the entire volume unless impossibly fine particles are included.

From the curves on the same graph we have contructed a histogram that gives the % weight of various size intervals. It is assumed that there are no particles smaller than ten microns. As an example from this histogram we see that particles between 25 and 50 μ account for 25% of the weight at the Surveyor VI site.

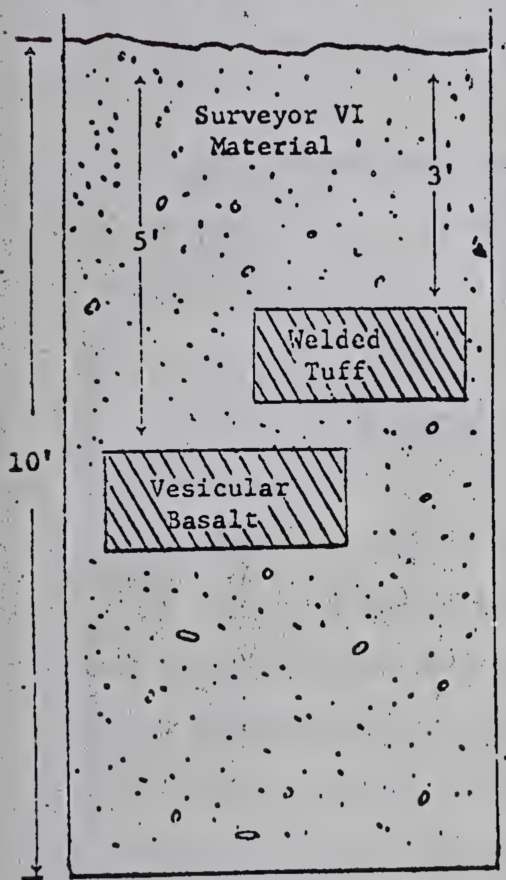
To make a mix more like that at Surveyor site I we adjust the frequency distribution of sizes above 1 mm so that it has a slope corresponding to Surveyor I results which account for approximately 14% of the weight. This adjusted histogram is shown on the same figure.

For the purpose of testing the drill we think it would be advisable to make three separate models;

Model 1 - This model will be at least 10 feet deep and have a particle mixture similar to that at Surveyor VI site and given in Figure 5 in terms of standard sieve sizes.

Model 2 - This model should have the same dimensions as Model 1 but simulate the size frequency distribution of Surveyor I site and shown in Figure 6.

Model 3 - The mixture used in this model would be the same as 1 but a tabular piece of welded tuff 50 cm thick would be buried 3 feet below the surface. At five feet below the surface a tabular piece of vesicular basalt 50 cm thick will be buried. Ideally the slabs would be buried so that either of both could be penetrated.



The bins that contain Models 1 and 2 should be provided with a door at the bottom so that they can be easily emptied and refilled.

It is further suggested that the material not be tamped after it is in the bin but be allowed to take a natural compaction after a fall of about two feet.

a. Drilling requirements:

The drilling requirements defined here assume that the heat flow holes will be drilled using a boron reinforced fiber glass drill stem. This material has a low enough thermal conductivity that it can be used both as the drill stem and casing sleeve. At this point in the development there are three possible approaches to accomplishing the stated objectives:

1. If both holes are drilled with a solid-faced bit, no core will be taken and the drilling task is reduced to driving two 3 meter drill stems into the lunar subsurface.

2. Use the boron reinforced fiber glass with a coring bit at one hole and the Lamont retrievable coreliner system to remove core samples during the drilling operation. Drill the second hole with a solid-faced bit.

3. After drilling two heat flow holes with solid-faced bits, at a third site close to the heat flow experiment, drill a 3 meter hole using titanium drill string. Retract the drill string and store those samples that have been retained.

Thus it is necessary to define the requirements for three possible approaches.

Case 1. No core is taken during this mission.

a. Drill two 3 meter holes using low conductivity drill stem and solid-faced bit (e.g. boron reinforced epoxy fiber glass) in the debris layer (regolith) of the lunar surface.

b. The drill stem used must have an internal diameter large enough to pass the lunar heat flow probes freely to the bottom with the aid of the emplacement tool.

c. The material of the drill stem will have a thermal conductance low enough so that it will not disturb the temperature gradient as measured by the heat flow probes in the undisturbed lunar soil by more than 10%. A stop will be provided at the bottom of the hole to position the lower heat flow probe at least five inches above the cutters of the drill core bit.

d. After completion of drilling, the drill stem will not protrude more than 20 inches above the lunar surface.

e. The drilling task should be accomplished with no more than twenty minutes of power-on time for the two holes.

Case 2. Core is retrieved during the drilling operation at the first hole.

a. Drill a 3 meter hole with a low conductivity drill stem and retrievable coreliner system in the lunar debris layer (regolith).

b. After completion of drilling of the first hole, the interior of the drill stem should be clear for at least 95% of the depth drilled so as to allow the heat flow probes to pass freely to within 5% of total depth drilled by the drill bit.

c. The thermal requirements remain the same as in Case 1. Except that there is no requirement for a stop at the bottom of the hole.

d. After completion of drilling, the drill stem will not protrude more than 20" above the lunar surface.

e. Drill the second hole with a solid-faced bit and low conductivity drill stem in the lunar debris layer. (The requirements are the same as those in Case 1.)

f. During the drilling of the first hole, core samples will be removed from inside the drill stem by means of six retrievable coreliners. These coreliners, which lock into the bottom section of the drill string, will be fitted at the lower end with a core-retaining mechanism so that 95% of the material that passes up into the liner during drilling is retained. The design of the coreliner and the core catcher should be such as to allow the drilled material passing through the core bit the least possible resistance upon entering the liner.

g. The coreliners will also serve as sample return containers fitted with airtight caps at their open ends. The liners are to be carried to the moon in the Lunar Sample Return Container and provision should be made to have them racked securely in this container.

h. Total power-on time for accomplishing this task will not exceed twenty minutes.

Case 3. Core samples are returned from a third hole.

a. Successfully complete the requirements of Case 1.

b. Using titanium drill string, drill a 3 meter hole. After drilling three meters or for a total power-on time of ten minutes, whichever comes first, the drill will be retracted.

c. The drill stem will be dismantled and both ends of each of the stem sections will be capped to reserve as sample return containers.

d. The titanium drill stem containing the core samples will be stowed in the Lunar Sample Return Container for the mission.

e. The third hole should be placed close enough to the two heat flow probes (within 3 meters) to obtain a sample of the regolith typical of the heat flow site. The third hole however should be no closer than two meters from either of the two heat flow holes.

b. Recommended drilling tests:

For Case 1:

a. Following a standard drilling procedure, demonstrate capability of drilling two 3 meter holes. One hole in the model simulating the Surveyor I distribution and the other in the Surveyor VI model.

Failure to complete this task might be expected if rocks totaling a thickness greater than one meter are encountered. This failure can be overcome by allowing longer power-on times, however this power-on time should not exceed the thickness of rock minus one meter divided by the average drilling rate.

Failure due to other structural or mechanical malfunctions are not acceptable.

b. Demonstrate the ability to penetrate 1/2 meter of vesicular basalt by drilling one ten-foot hole in model three.

<u>For Case 2</u>:

a. Following a standard drilling procedure demonstrate capability of drilling and retrieving core from a 3 meter hole in the model containing the Surveyor VI mix.

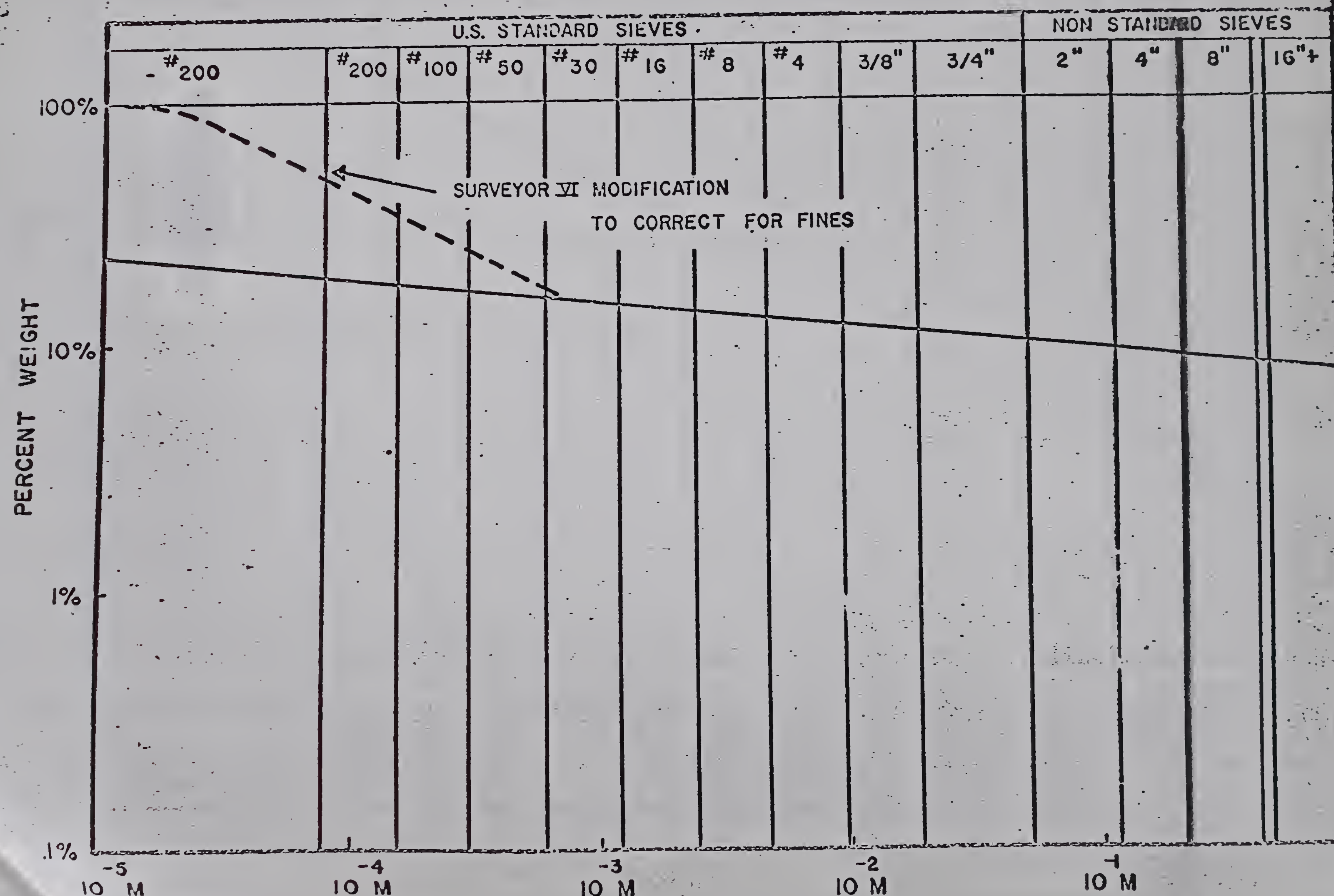
<u>For Case 3</u>.

Same tests as in Case 1 - Tests of the titanium drill stem can be considered satisfied by earlier ALSD testing.

SURVEYOR I

Sieve No. US Standard	Particle Pass Size in	mm	% Weight Actual		Adjusted	
None	20	508	8.60		1.37	
None	16	464	.60		1.37	
None	8	232	.65		1.48	
None	4	116	.75		1.71	
None	2	50.8	1.10	8% not spread	2.51	8% spread over this range
3/4	3/4	19.0	.70		1.60	
3/8	3/8	9.51	.90		2.06	
#4	0.187	4.76	.90		2.06	
#8	0.937	2.38	.90		.90	
#16	0.469	1.19	2.20		2.20	
#30	0.234	0.595	7.5		7.5	
#50	0.117	0.297	9.7		9.7	
#100	0.0059	0.149	14.0		14.0	
#200	0.0029	0.074	51.5		51.5	

SURVEYOR I PARTICLE SIZE DISTRIBUTION



SURVEYOR VI PARTICLE SIZE DISTRIBUTION